Soil Aluminum Effects on Growth and Nutrition of Cacao

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Received March 29, 2004; accepted in revised form January 11, 2005

In acid soils, Al toxicity and nutrient deficiencies are main constraints for low yield of cacao (*Theobroma cacao* L.). A controlled growth chamber experiment was conducted to evaluate the effect of three Al saturations (0.2, 19, and 26%) adjusted by addition of dolomitic lime on growth and nutrient uptake parameters of cacao. Overall, increasing soil Al saturation decreased shoot and root dry weight, stem height, root length, relative growth rate, and net assimilation rate. However, increasing soil Al saturation increased leaf area, specific leaf area (total leaf area/total leaf dry wt), and leaf area ratio (total leaf area/ shoot+root wt). Increasing soil Al saturation decreased uptake of elements. Nutrient influx (IN) and transport (TR) decreased significantly for K, Ca and Mg, and showed an increasing trend for S and P as soil Al saturation increased. However, increasing soil Al saturation significantly increased nutrient use efficiency ratio (ER, mg of shoot weight produced per mg of element in shoot) of Ca, Mg and K and decreased ER for other elements. Reduction of soil acidity constraints with addition of lime and fertilizers appear to be key factors in improving cacao yields in infertile, acidic, tropical soils.

Key Words: **net assimilation rates, nutrient influx and transport, nutrient use efficiency, relative growth rate, *Theobroma cacao*.**

Cacao (*Theobroma cacao* L.) is grown on wide range of soil types and often these soils are leached, acidic and low in P, N, Ca, Mg and other essential nutrients (Hardy 1960; Smyth 1966; Wood and Lass 2001). Cacao grown soils have become infertile and more acidic due to lack of proper fertilizer and liming practices, long term cultivation and use of other inappropriate management practices (Hardy 1960; Smyth 1966; Wessel 1971; Wood and Lass 2001). In highly weathered tropical soils, loss of nutrients through erosion and leaching has accelerated soil degradation and exhaustion of essential nutrients (Baligar and Fageria 1997; Sanchez and Salinas 1981).

In West Africa and Brazil cacao is widely grown on either neutral or slightly acidic soils (Santana and Cabala-Rosand 1984). In east Malaysia, on granitic soils, poor cacao performance was related to high soil acidity and exchangeable Al and low base saturation, and exchangeable Ca (Ng et al. 1970). In acidic soils, the toxicities of Al, Mn and H and deficiency of essential nutrients are largely responsible for low yields of cacao (Wessel 1971; Santana and Cabala-Rosand 1984; Nakayama et al. 1987, 1988; Cabala-Rosand et al. 1989). Under field conditions, Al saturation higher than 15% appears to be toxic to cacao growth (Santana et al. 1971; Wood and Lass 2001). Nakayama et al. (1987, 1988) reported significant improvement in biomass production in cacao grown on Oxisols and Ultisols due to liming.

Deficiency of P, Ca, Mg, Zn and Fe in cacao culture have been reported (Cabala-Rosand et al. 1989; Wilson 1999). Cacao reported to have higher nutrient requirements than other plantation crops when grown on infertile acidic soils (Cabala-Rosand et al. 1989). Differences in nutrient uptake and use efficiency and growth among plant species have been related to shoot demand for nutrients and dry matter production potentials per unit of nutrient absorbed (Baligar and Fageria 1997; Baligar et al. 2001). However, there are limited published work relating cacao growth in acid soils and its nutrient demand. Acidity is a major degradation factor of soils under cacao. Soil acidity constraints, especially high levels of soil exchangeable Al on growth and mineral nutrition of cacao are not well understood. The objectives of present study were to evaluate the effects of varying soil Al saturations on growth (shoot and root growth, root length, leaf morphological parameters, shoot/root ratio, relative growth rate, net assimilation rate) and nutrient uptake (uptake, influx, transport, nutrient use efficiency ratio) parameters of cacao.

MATERIALS AND METHODS

Soil and Al saturations. Acidic Porter soil (coarse-loamy, mixed mesic, Umbric Dystrochrept) from Tennessee (USA) was used. Three levels (26, 19, and 0.2%) of Al saturations were obtained by mixing soil with 0.5, 2.0, and 10 g kg^{-1} of dolomitic lime. To all Al treatments, a basal fertilizer of 75 mg N, 100 mg P, 100 mg K, 5.0 mg Zn, 5.0 mg Cu, 1.0 mg B, and 0.1 mg Mo was applied per kg of soil and incubated for 3 weeks at 33 kPa moisture tension. Addition of the 3 levels of dolomitic lime and the basal fertilizer to soil resulted pHw of 4.3, 4.4 and 5.3; exchangeable Ca (cmol kg^{-1}) of 1.3, 1.6 and 4.6; exchangeable Mg (cmol kg^{-1}) of 0.59, 1.24 and 4.58 and H+Al (cmol kg^{-1}) of 4.14, 3.09 and 0.22 and Bray-1 P (μg g^{-1}) 25, 27 and 22, respectively. Soil chemical analysis was done at the A & L Eastern Agricultural Lab, Richmond, VA†. Exchangeable cations were determined by adapting methods of Knudsen et al. (1982) and Lanyon and Heald (1982), exchange acidity and Al were determined by Yuan (1959) method and P was determined by adapting Olsen and Sommers (1982) method.

Growth conditions. Pods of cacao "comum" cultivar were received from Brazil. Seeds were removed from pods and planted in sand and perlite mixture (1:1 volume). Seedlings were raised in the greenhouse and on d 10, were transplanted to 2 kg capacity plastic pots containing soil having various levels of Al saturation. Plants were grown in a growth room at 28°C temperature, 75% RH, with photosynthetic photon flux density (PPFD) of 350 μmol m^{-2} s^{-1}, for 14 h d^{-1}. All experimental units were replicated 5 times. Plants were grown for 90 d and at harvest. At harvest, leaf area (Li-Cor model 300 leaf area meter, Li-Cor Inc., Lincoln, NE) and root length (Comair Root Length Scanner, Hawker de Haviland, Melbourne, Victoria, Australia) were recorded. Shoots and roots were washed in deionized water, blotted dry, oven dried at 70°C for 5 d and weighed. Chemical analysis of the shoot samples was done at the A & L Southern Agricultural Lab, Pompano Beach, FL. Plant elemental compositions were determined by adapting the modified methods suggested by Wolf (1982). Briefly, shoot samples were wet digested in concentrated sulfuric acid and 30% hydrogen peroxide for elemental determination. Sulfur was determined by digesting plant samples in a muffle furnace at 600°C, with magnesium nitrate and dissolving the ash in HCl. Cations were determined by an Atomic Absorption Spectrometer (Perkin Elmer Analyst 400). N, S, and P were determined by a spectrophotometer (Gilford STASR II).

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Determination of growth and nutrient uptake parameters. The following growth parameters are based on measurements on plants made at harvest on 90 d of growth. For RGR, NAR, IN and TR determinations, an initial harvest was made on the 10th d of growth.

Specific Leaf Area (SLA, cm^2 g^{-1})=[Total leaf area, cm^2 / Total leaf dry wt, g]

Leaf Area Ratio (LAR, cm^2 g^{-1})=[Total leaf area, cm^2/ Shoot+Root wt, g]

Leaf/Shoot Ratio (L/S)=[Leaf dry wt/Shoot dry wt]

Root/Shoot Ratio (R/S)=[*Wr*/*Ws*], where *Wr* is root wt and *Ws* is shoot wt.

Relative Growth Rate (RGR)=[ln $(Wt_2/Wt_1)/(T_2 - T_1)$], where, *Wt* is total wt (shoot+root), T is time in d, 1 and 2 refer to initial and final harvest.

Net Assimilation Rate (NAR)=[RGR/LAR]

Nutrient Influx (IN) = $[(U_2-U_1) / (T_2-T_1)]$ $[(\ln Wr_2 - \ln Wr_1) / (Wr_2-Wr_1)]$, where, *U* refers to elemental content in shoot (mmol/plant) and *T* is time in s, subscripts 1 and 2 refer to initial and final harvest time.

Nutrient Transport (TR)=$[(U_2-U_1) / (T_2-T_1)]$ $[(\ln Ws_2 - \ln Ws_1)/(Ws_2-Ws_1)]$

Nutrient Use Efficiency Ratio (ER)=[mg of *Ws*/mg of any given element in shoot]

Details of the methods used for determination of plant growth, nutrient uptake and physiological parameters were described by Ziska and Bunce (1994), Baligar and Fageria (1997), Bunce (1997) and Baligar et al. (2001). Data were subjected to analysis of variance using a general linear model (GLM) procedures of SAS (Ver. 8, SAS Institute, Cary, NC).

RESULTS AND DISCUSSION

Growth parameters

In many tropical acid soils, toxic levels of H, Al and Mn and deficient levels of essential nutrients such as Ca, Mg, N, P and micronutrients are probable major factors for low yields of cacao (Wessel 1971; Santana and Cabala-Rosand 1984; Nakayama et al. 1987, 1988; Cabala-Rosand et al. 1989). In our experiment, increasing soil Al saturation decreased shoot and root biomass, stem height, root length, relative growth rate (RGR) and net assimilation rates (NAR) (Table 1). In pot studies, cacao has shown a negative correlation between biomass production and soil Al saturation (Santana and Cabala-Rosand 1984). Increasing soil Al saturation tended to decrease leaf wt; however it increased leaf area (LA), specific leaf surface area (SLA), leaf wt/shoot wt ratio (L/S) and leaf area ratio (LAR). These results suggested that soil acidity tended to reduce the thickness of leaves, but increased their surface area. However soil Al saturations had significant effects only on biomass accumulation of shoot and root, SLA, LAR, RGR and NAR. It has been extensively reported that the poor productivity of plants grown in acid soils is due to combinations of toxicities (Al, Mn and H) and deficiencies of essential

Table 1. Effect of soil Al levels on shoot and root growth parameters of cacao.

Parameters		% Soil Al saturation			Significance
		26	19	0.2	
Shoot wt	g plant^{-1}	4.17	4.82	5.48	*
Root wt	g plant^{-1}	0.99	1.01	1.38	*
Stem ht	cm plant^{-1}	30.70	33.50	32.50	NS
Root length	m plant^{-1}	31.24	26.92	34.98	NS
Leaf area	cm^2 plant^{-1}	798	729	777	NS
Leaf wt	g plant^{-1}	2.83	3.18	3.50	NS
SLA	cm^2 g^{-1}	283.06	230.75	223.67	**
LAR	cm^2 g^{-1}	156.71	125.84	113.23	*
L/S		0.68	0.66	0.64	NS
R/S		0.24	0.21	0.25	NS
RGR$\times 10^{-2}$	g g^{-1} d^{-1}	2.80	2.90	3.10	*
NAR$\times 10^{-4}$	g cm^{-2} d^{-1}	1.83	2.35	2.77	**

* and ** Denote values in each row are significant at 0.05 and 0.01 levels of probability, respectively. NS=Not significant.

nutrients (N, P, Ca, Mg, Fe, and Zn) (Foy 1984). In acid soils liming has improved cacao growth (Nakayama et al. 1987, 1988).

Nutrient uptake (U) and efficiency ratio (ER)

With the exception of K there is a decline in all essential nutrients in a soils under long term cocoa cultivation (Hardy 1960; Wessel 1971; Wilson 1999; Wood and Lass 2001). In our study the uptake of elements decreased with increasing soil Al saturation; however, significant differences were observed only for the uptake of K, Ca and Mg (Table 2). Low nutrient uptake by plants in acid soils is due to the presence of high levels of Al and H which interfere with uptake of P, K, Mg and Ca, and to Al toxicity which limits root growth (Foy 1984; Fageria and Baligar 2003). Aluminum toxicity creates shallow roots and low root density, thereby hindering the ability of plants to explore a large enough soil volume to obtain many essential elements required for growth (Foy 1984; Baligar and Fageria 1997; Keltjens 1997). Al toxicity induces formation of thick roots which are less efficient in taking up nutrients such as P (Keltjens 1997). In the present study reduction of exchangeable Al from 26 to 0.2 cmol kg^{-1} by addition of dolomitic lime increased the root and shoot biomass accumulation by cacao. Significant improvement in biomass production in cacao was achieved by liming of acidic Oxisols and Ultisols soils of Bahia, Brazil (Nakayama et al. 1987, 1988). In their study, liming of Ultisols reduced concentrations of Mn and Zn and increased concentrations of N, P, K, Ca and Mg in cacao. Phosphorus is the major limiting nutrient in almost all soils in which cacao is grown (Ahenkorah 1981). In many parts of the world deficiencies of P, Ca, Mg, Zn and Fe in cacao have been widely reported (Loue 1961; Cabala-Rosand et al. 1989; Wilson 1999). In the present study lime application to acid soil improved uptake of P, Ca, and Mg by cacao.

Differences in nutrient uptake and use efficiency among plant species have been related to dry matter production potentials per unit of nutrient absorbed, nutrient absorption, translocation and shoot demand (Baligar et al. 2001). Increasing soil Al saturation significantly increased the ER for Ca, Mg, and K (Table 2). However with few exceptions overall increasing soil Al saturations tended to decrease ER for N, P and S. Nutrient demand by plants for any given nutrient is a function of its rate of growth and internal ionic concentration (Baligar et al. 2001). Reduction in biomass accumulation in shoot due to presence of phytotoxic levels of Al in growth medium reduced cacao demand for nutrients and lowered its nutrient uptake. Long-term intensive cacao cultivation, non existence or inadequate fertilizer and lime inputs and loss of nutrients through erosion and leaching invariably lead to degradation of land and lowering of soil fertility and cacao productivity (Wood and Lass 2001). Therefore, soil amendments that enhance soil fertility and reduces soil acidity could improve ER for essential nutrients in plants. Improved ER for essential nutrients could enhance production of cacao grown on degraded infertile soils. The ER values are useful in assessing the ability of plants to use absorbed nutrients efficiently or non-efficiently and also as a tool to screen for more efficient cultivars.

Table 2. Effect of soil Al levels on uptake (U, mg plant^{-1}) and nutrient use efficiency ratios (ER, mg shoot/mg^{-1} element in shoot) of macronutrients in cacao.

Elements	% Soil Al saturation						Significance	
	26		19		0.2			
	U	ER	U	ER	U	ER	U	ER
N	83.03	50.3	83.86	58.8	100.07	55.0	NS	NS
P	4.48	965.2	5.22	970.6	4.67	1194.4	NS	NS
S	4.78	873.2	4.55	1,072.2	5.42	1,020.7	NS	NS
K	63.21	65.8	71.00	70.1	104.23	52.6	**	*
Ca	32.50	128.0	53.33	90.9	57.12	95.4	**	**
Mg	20.91	199.0	33.25	145.0	41.85	135.7	**	**

* and ** Denote values in each row are significant at 0.05 and 0.01 levels of probability, respectively. NS=Not significant.

Nutrient influx (IN) and transport (TR)

With few exceptions, increasing soil Al saturation tended to increase IN for N and S, and decrease IN for K, Ca, and Mg (Table 3). Influx for P increased with decrease in soil Al saturation from 26% to 19% and then decreased with further decrease in soil Al saturation. Increasing soil Al saturation tended to increase TR for S and decreased TR for K, Ca and Mg (Table 3). The TR for P slightly increased with decrease in soil Al saturation from 26% to 19% and a further decrease in soil Al saturation reduced TR for P. However, TR for N decreased as soil Al saturation decreased from 26% to 19% but further reduction in Al saturation to 0.2% increased the TR. Overall, soil Al saturations had significant effects only on the IN and TR of K, Ca and Mg. No previous information is available on the influence of

Table 3. Effect of soil Al levels on influx (IN, pmol g root^{-1} s^{-1}) and transport (TR, pmol g shoot^{-1} s^{-1}) of macro nutrients in cacao.

Elements	% Soil Al saturation						Significance	
	26		19		0.2			
	IN	TR	IN	TR	IN	TR	IN	TR
N	1,770	470	1,730	427	1,710	472	NS	NS
P	31	8	40	9	25	7	NS	NS
S	44	12	41	9	41	11	NS	NS
K	441	118	494	121	620	171	*	*
Ca	244	65	494	99	354	98	**	**
Mg	259	69	421	102	418	116	*	**

* and ** Denote values in each row are significant at 0.05 and 0.01 levels of probability, respectively. NS=Not significant.

Al on IN and TR of essential nutrients in cacao. Interaction of plant genetic and physiological components with properties and nutrient status of soil profoundly affect the plants ability to acquire and transport nutrients (Gerloff and Gabelman 1983; Vose 1984; Baligar and Fageria 1997). Root morphological parameters such as length, surface area, volume and dry weight, and physiological condition of plants, such as nutrient demand and rate of growth are known to profoundly influence the nutrient uptake parameters (U, IN, TR) (Baligar and Fageria 1997; Keltjens 1997; Baligar et al. 2001). Aluminum is known to affect the physiological parameters of shoot and roots (Foy 1984). In the current study, higher soil Al saturations reduced root biomass and root length and such reduction might have contributed to reduced IN of slow diffusing cations such as Ca, Mg and to some extent K near the root soil interphase (Baligar and Fageria 1997).

Acknowledgments. We thank S. Faulkner and J. Mascio for excellent technical support, J. Fisher for statistical analysis and C.D. Foy, J.L. Ahlrichs, I.P. Oliveira and M.P. Barbosa Filho for critical comments. We thank Alan Pomella, Almirante Cacao Center Itajuipe, Bahia Brazil, for providing cacao pods.

REFERENCES

Ahenkorah Y 1981: The influence of environment on growth and production of the cacao tree: Soils and nutrition. Proceeding of 7th International Cocoa Research Conference, Douala, Cameroon, p. 167–176

Baligar VC and Fageria NK 1997: Nutrient use efficiency in acid soils: Nutrient management and plant use efficiency. *In* Plant Soil Interactions at Low pH, Ed. AC Monez et al., p. 75–95, Brazilian Soil Sci. Soc., Compinas, Brazil

Baligar VC, Fageria NK, and He ZL 2001: Nutrient use efficiency in plants. *Commun. Soil Sci. Plant Anal.*, **32**, 921–950

Bunce JA 1997: Variation in growth stimulation by elevated carbon dioxide in seedlings of some C_3 crop and weed species. *Global Change Biol.*, **3**, 61–66

Cabala-Rosand P, Santana MBM, and Santana CJL de 1989: Cacao. *In* Detecting Mineral Nutrient Deficiencies in Tropical and Temperate Crops, Ed. DL Plucknett and HB Sprague, p. 409–425, Westview Tropical Agriculture Series, Westview Press, London

Fageria NK and Baligar VC 2003: Fertility management of tropical acid soils for sustainable crop production. *In* Handbook of Soil Acidity, Ed. Z Rengal, p. 359–385, Marcel Dekker, New York

Foy CD 1984: Physiological effects of hydrogen, aluminum, and manganese toxicities in acid soils. *In* Soil Acidity and Liming. Monograph 12, 2nd Ed., Ed. F Adams, p. 57–97, American Society of Agronomy, Madison WI

Gerloff GC and Gabelman WH 1983: Genetic basis of inorganic plant nutrition. *In* Inorganic Plant Nutrition, Ed. A Lauchli and RL Bielski, p. 453–480, Springer-Verlag, New York, NY

Hardy F 1960: Cacao Manual. Inter-American Institute of Agriculture Science, Turrialba, Costa Rica

Keltjens WG 1997: Plant adaptation and tolerance to acid soils; Its possible Al avoidance—A review. *In* Plant Soil Interactions at Low pH, Ed. AC Monez et al., p. 109–117, Brazilian Soil Sci. Soc., Campinas, Brazil

Knudsen D, Peterson GA, and Pratt PF 1982: Lithium, sodium, and potassium. *In* Methods of Soil Analysis. Part 2: Chemical and Microbiological Properties (Spec. Pub. No. 9, 2nd Ed.), Ed. AL Page et al., p. 225–246, American Society of Agronomy and Soil Science Society of America, Madison, WI

Lanyon LE and Heald WR 1982: Magnesium, calcium, strontium, and barium. *In* Methods of Soil Analysis. Part 2: Chemical and Microbiological Properties (Spec. Pub. No. 9, 2nd Ed.), Ed. AL Page et al., p. 247–262, American Society of Agronomy and Soil Science Society of America, Madison, WI

Loue A 1961: Mineral deficiencies and shortages in cacao. French Institute for Coffee and Cacao (IFCC) Bulletin No. 1

Nakayama LHI, Pinto LRM, and Santana, CJL 1987: The effect of lime application on the cultivation of cacao (*Theobroma cacao* L). Proceedings of the 10th International Cocoa Research Conference, Santo Domingo, Dominican Republic, p. 259–264

Nakayama LHI, Santana De CJL, and Pinto LRM 1988: Response of young cacao plants to liming. *Revista Theobroma*, **18**, 229–240

Ng SK, Thamboo S, and Cheah TE 1970: Soil and leaf nutritional status of cacao on the east and west coasts of Malaya. *Malaysian Agric. J.*, **47**, 390–408

Olsen SR and Sommers LE 1982: Phosphorus. *In* Methods of Soil Analysis. Part 2: Chemical and Microbiological Properties (Spec. Pub. No. 9, 2nd Ed.), Ed. AL Page et al., p. 403–430, American Society of Agronomy and Soil Science Society of America, Madison, WI

Sanchez PA and Salinas JG 1981: Low-input technology for managing Oxisols and Ultisols in tropical America. *Adv. Agron.*, **34**, 279–406

Santana CJL and Cabala-Rosand P 1984: Soil acidity and cacao response to lime application in South Bahia, Brazil. Proceeding of the 9th International Cocoa Research Conference, Lome, Togo, p. 199–203

Santana MBM, Cabala-Rosand FP, and Morais FI De O 1971: Effects of increasing levels of lime on some soils of cocoa growing region of Bahia. *Revista Theobroma*, **1**, 17 –28

Smyth AJ 1966: The selection of soils for cocoa. Soils Bull 5, Food and Agricultural Organization of the United Nation Rome

Vose PB 1984: Effects of genetic factors on nutritional requirement of plants. *In* Crop Breeding: A Contemporary Basis, Ed. PB Vose and SG Blixt, p. 67–114, Pergamon Press, Oxford, UK

Wessel M 1971: Fertilizer requirements of cocoa (*Theobroma*

cacao L) in South-Western Nigeria. Communication 61, Department of Agricultural Research, Royal Tropical Institute, Wageningen, The Netherlands

Wilson K 1999: Coffee, Cocoa and Tea, CABI Publishing, Oxon, UK

Wolf B 1982: A comprehensive system of leaf analysis and its use for diagnosing crop nutrient status. *Commun. Soil Sci. Plant Anal.*, **13**, 1035–1059

Wood GAR and Lass RA 2001: Cocoa, 4th Ed., Blackwell Science, Oxford, UK

Yuan TL 1959: Determination of exchangeable hydrogen in soils by titration methods. *Soil Sci.*, **88**, 164–167

Ziska LH and Bunce JA 1994: Increasing growth temperature reduces the stimulatory effects of elevated CO_2 on photosynthesis or biomass in two perennial species. *Physiol. Plant.*, **91**, 183–190